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TITLE OPERATING EXPERIENCE WITH A 100-KeV, 100-mA  $H^-$  INJECTOR

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# EXPERIMENTAL

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## OPERATING EXPERIENCE WITH A 100-keV, 100-mA H<sup>-</sup> INJECTOR\*

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### ABSTRACT

According to beam dynamics calculations it should be possible to accelerate a high-perveance beam in a radio-frequency quadrupole (RFQ) accelerator with low emittance growth and nearly 100% capture efficiency. A 100-mA, 100-keV H<sup>-</sup> ion injector with a 5-Hz, 1-ms duty factor was built for use with this accelerator, but the beam emittance at 100 keV was found to be two to four times the value previously determined at 20 keV. This emittance growth was traced to the 20-keV beam transport, where an instability occurred in the background plasma created by beam ionization of the residual gas. The injector has been rebuilt with a shorter transport length, resulting in greatly reduced emittance growth.

### ORIGINAL INJECTOR

The first version of the injector was intended to provide a 250-keV, 20-mA beam for studies with a drift-tube linac. Beam was extracted from a Penning source with a circular aperture<sup>1</sup>, focused with a 90°,  $n = 0.5$  dipole magnet and with a quadrupole doublet before reaching an emittance station in front of the column, 60 cm from the source (Fig. 1). With the successful test of an RFQ at Los Alamos<sup>2</sup> the injector was modified to produce a 100-mA, 100-keV beam. A 10- by 0.5-mm slit was used as the beam emitter, the magnet was changed to  $n = 0.9$ , and the column was shortened to provide a higher gradient. The Y-axis is along the 10-mm direction of the slit. Calculations still indicated favorable beam transport, assuming complete space-charge neutralization of the beam.

Emittances were measured with an electric-sweep scanner,<sup>3</sup> and the results quoted here are rms normalized values, as calculated in the computer analysis according to the formula<sup>4</sup>

$$\epsilon_x = \epsilon_y \sqrt{\frac{x^2 + x'^2}{y^2 + y'^2}}.$$

The first measurements showed that only about half of the extracted current was transmitted to the accelerating column entrance (Fig. 1). Experiments with various commonly available gases, ranging from hydrogen to xenon, showed that beam transmission could be dramatically increased by flooding the transport system with xenon, with lighter gases giving poorer results. Measured transmissions at

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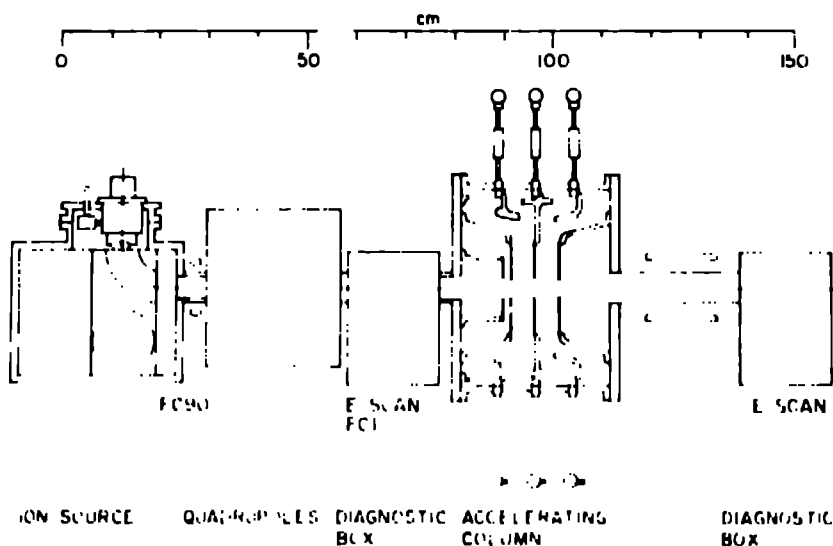


Fig. 1. Layout of original 250-keV, 20-mA injector, modified for use at 100-keV, 100-mA operation.

the 90° magnet exit (FC90) and at the column entrance (FC1) are shown in Fig. 2 as a function of neon and of xenon densities. Also shown are the calculated currents, assuming full transmission from extraction except for stripping losses. These results can be partially understood by comparing the stripping losses at the Gabovitch critical density<sup>4</sup> for the various gases (Table I). At lower densities, a negative ion beam will be underneutralized, according to his theory. It is seen that stripping losses for light gases are substantially higher than for heavy gases. Improved beam transmission then presumably results from a balance between the beam's stripping losses and reduced effective space charge. Much more troublesome was the emittance growth. Whereas the emittance of the beam from the 10 by 0.5-mm slit was found to be  $10.0 \times 10^{-1}$  by  $0.01$  ( $\pi$  cm-mrad) 20 cm from the source, it was typically  $0.07$  by  $0.03$  at the emittance scanner 60 cm from the source. An interesting observation had been that the emittance scanner currents (proportional to the phase space

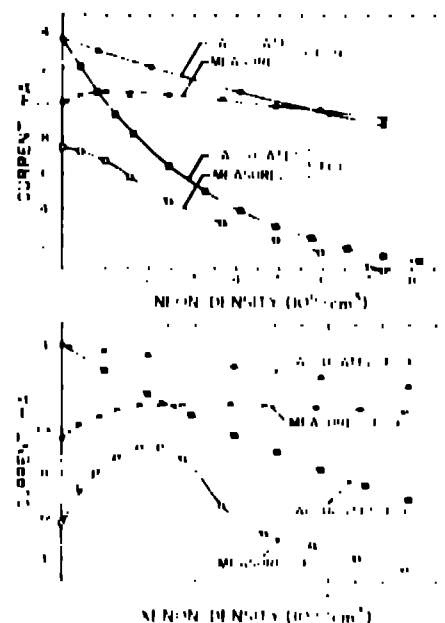


Fig. 2. Measured and calculated beam transmission from extraction to the 90° magnet exit (FC90) and the column entrance (FC1) versus densities of neon and xenon gases.

TABLE I

PROPERTIES OF GASES FOR H<sup>-</sup> BEAM NEUTRALIZATION AT 20 keV

| Gas/amu            | $n_{an}$<br>( $10^{12}/\text{cm}^3$ ) | Losses<br>$n_{an}(\gamma-10+e-11)$ | $\sigma_i(10^{-16} \text{ cm}^2)$ |
|--------------------|---------------------------------------|------------------------------------|-----------------------------------|
|                    |                                       | (%/cm)                             |                                   |
| H <sub>2</sub> /2  | 23.6                                  | 2.12                               | 1.5                               |
| He/4               | 66.4                                  | 3.14                               | 0.38                              |
| Ne/20              | 16                                    | 0.88                               | 0.7                               |
| N <sub>2</sub> /28 | 2.38                                  | 0.33                               | 4                                 |
| O <sub>2</sub> /32 | 2.7                                   | 0.34                               | 3.3                               |
| Ar/40              | 1.7                                   | 0.29                               | 4.7                               |
| Kr/83.8            | 1.03                                  | 0.32                               | 5.4                               |
| Xe/131.3           | 0.59                                  | 0.23                               | 7.6                               |

$n_{an}$  = gas density for exact neutralization (Gaborvitch critical density)

$$= 2\sqrt{8kT_i/\pi} M_i / Rv_{\perp} \sigma_i \text{ where}$$

$T_i$  = ion temperature  $\sim 0.1$  eV

$M_i$  = mass of neutralizing gas

$R$  = beam radius = 1 cm

$\sigma_i$  = cross section for ionization of gas by H<sup>-</sup> ion

densities), had much greater fluctuation than the beam current itself, and that the amplitude of fluctuations was progressively larger farther along the transport toward the RIG. Dhabbarov<sup>6</sup> has reported beam-plasma oscillations produced by an H<sup>-</sup> beam with conditions similar to those in our injector, and he showed that oscillations in current and in beam potential were damped at high argon density in the transport line. In accordance with Dhabbarov's results, we examined the effects of much higher density of xenon.

The 20-keV emittance scanner (Fig. 1) was positioned in the beam center, and the scanner current, proportional to  $d^2n/dx dx_y$  as a function of  $x'$ , was recorded for 50 beam pulses for low and for high xenon density. The extracted current (Fig. 3a) did not change significantly and had 5-10% fluctuation; however, the phase space rotated and shrank at high density (Fig. 3b). The most interesting change was a substantial reduction in the pulse-to-pulse fluctuations in the phase space density, (Fig. 3c). We found that the emittance decreased markedly in the two planes as a function of xenon density (Fig. 4). Excessive stripping losses with high xenon density made this method of emittance control unacceptable. It may also be that the beam plasma cannot adjust fast enough to track the variations in current. We calculated that if the effective current varied by 13 mA about zero, then the resulting phase space orientations, averaged in time, would account for the observed emittance growth. The neutralization time constant varied from about

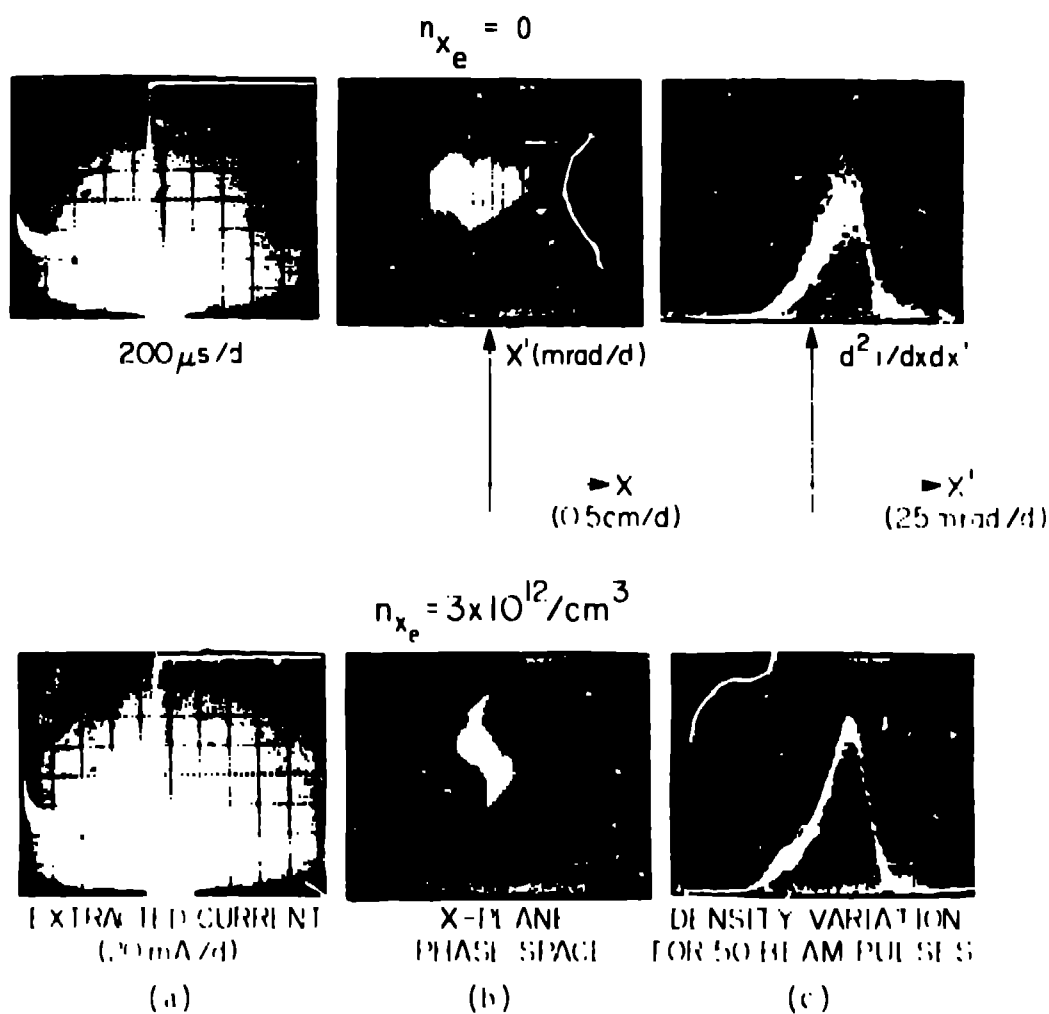
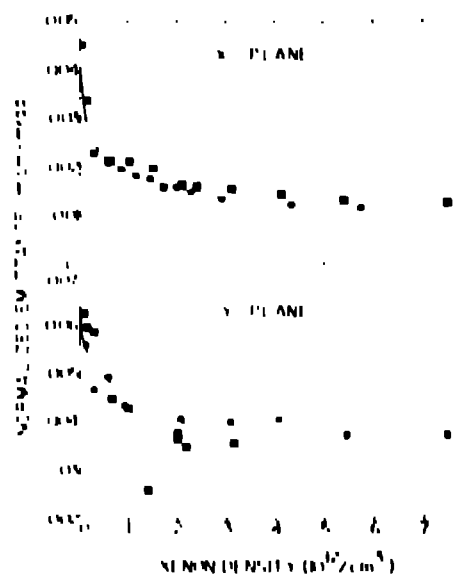


Fig. 3. (a) Waveform of extracted current, (b) phase-space contour plot in X-plane, (c) phase-space density variation for 50 consecutive beam pulse in the X-plane.

Fig. 4. Emittance variation at column entrance vs. xenon density. Circles and squares are for slightly different source operation.



2 ns at  $4 \times 10^{12}/\text{cm}^3$  with xenon to about 30 ns with only residual hydrogen--about the right range for this effect because the observed beam fluctuations are mostly below 1 MHz. Considerations<sup>7</sup> of the likely beam-plasma densities, however, suggest that there will be adequate electrons present to accommodate the oscillations. The cause of the emittance growth is therefore unclear from our measurements; however, a solution to the problem seemed clear: reduce the length of the beam-transport line.

#### REVISED INJECTOR

The primary objective of rebuilding the injector was to shorten the 20-keV transport as much as possible. With a shortened transport line, a high density of xenon does not lead to excessive beam stripping. We believed that direct extraction at 100 keV was not desirable for our slit emitter source, so a new 20-keV source was built, using samarium-cobalt permanent magnets. In the configuration chosen (Fig. 5), the physical length of the magnet structure extends only 35 mm from the emission slit, and the bend angle at 22-keV energy is  $8.1^\circ$ . This allows refocusing or further accelerating with a minimum of drift, and the second-order aberrations of the magnet are negligible. The effect of energy dispersion is greatly reduced, and it is possible to measure beam emittance much closer to extraction than before.

The source performance was investigated on a separate test stand at 20-keV extraction energy 92 mm from the emission slit,

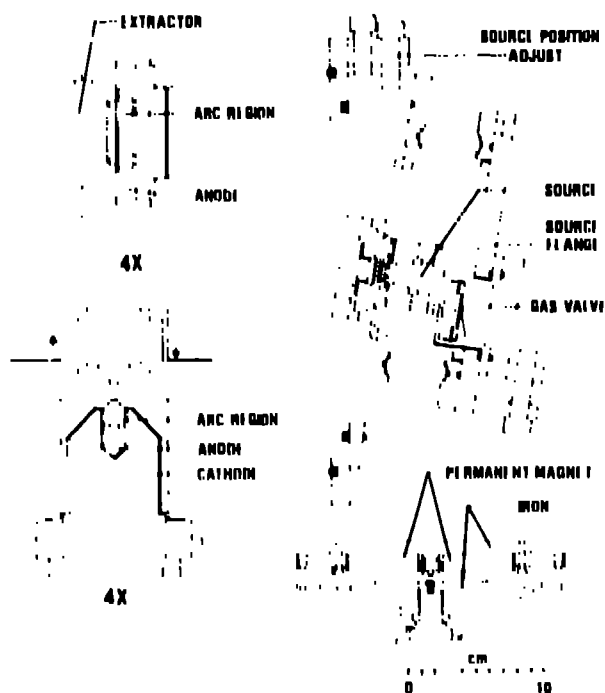


Fig. 5. Schematic of small angle source (SAS).

about twice the length of the new injector 22-keV transport, so instabilities in the neutralizing gas presumably would be more severe than on the injector. Within the 25% scatter of our measurements, there was no effect on emittance of xenon density from  $0-6 \times 10^{12}/\text{cm}^3$ . There was a definite effect on the phase-space orientation, however, indicating that the beam is generally under-neutralized with only residual gas. The emittance at 150 mA is  $0.027 \text{ cm} \cdot \text{mrad}$  in the Y-plane by less than 0.004 in the X-plane. Over 180-mA current has been extracted, and the noise in a 1-MHz bandwidth has been as low as 0.2% (Fig. 6a). The phase-space densities in the two planes near the beam center line are also shown

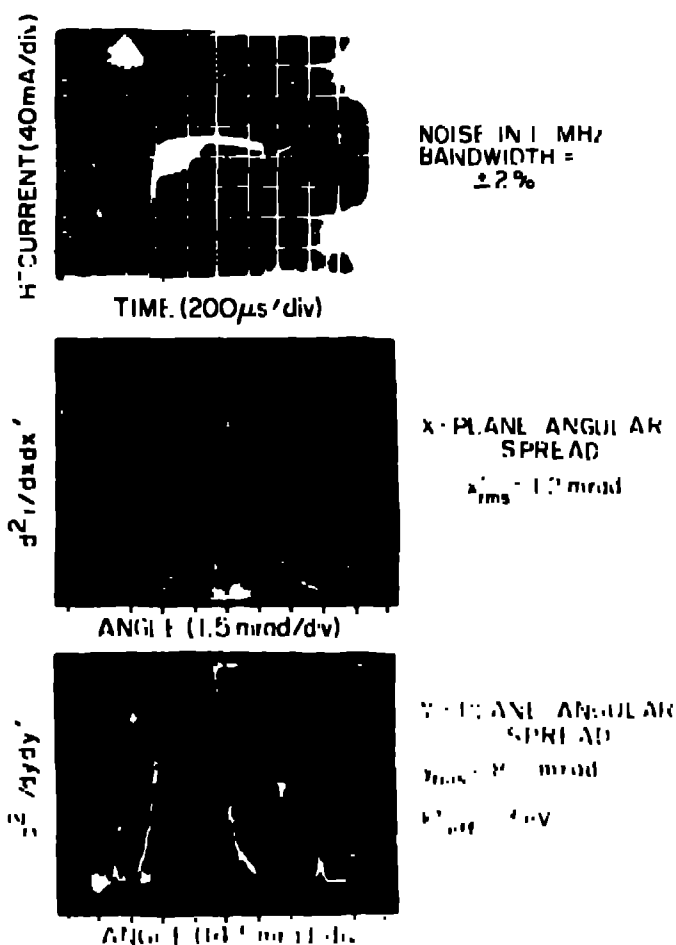


Fig. 6. (a) Waveform of 180-mA beam pulse from the SAS, (b) angular spread in the X-plane, (c) angular spread in the Y-plane.

(Fig. 6b and 6c). In the narrow and diverging plane,  $\Delta x'_{rms} = 1.2$  mrad is typical. In the large plane, the beam is nearly parallel (with a size about equal to the slit width) so that the angular spread at the scanner is close to that at the plasma. The value  $\Delta y'_{rms} = 8.3$  mrad then can be used to calculate for the H<sup>+</sup> ions that  $kT_{eff} = 3$  eV from  $kT = 2e(\Delta y'_{rms})^2$ , where  $d$  is the beam voltage. The small peaks in the  $y'$  distribution (Fig. 6c) are from ions coming from the ends of the 10-mm slit; thus, the width of the main peak is seen to be unaffected by end effects.

The original accelerating column was replaced with a shorter system. Favorable results from optical calculations and the desire to minimize emittance growth in the 20-keV transport in the column led us to couple the source as closely as possible to the column. An electron suppressor electrode at the entrance is followed by the accelerating gap (Fig. 7). Beam current, as measured at the Faraday cup 46 cm from the source, is about as expected. At the design arc current of 200 A, we measured over 140 mA of current at 100-keV energy.

At an arc current of 160 A, a substantial set of 100-keV emittance measurements were made. Emittance was found to increase with electron suppressor voltage in approximate agreement with emittance-growth calculations made with the SNOW<sup>8</sup> code. Current transmitted

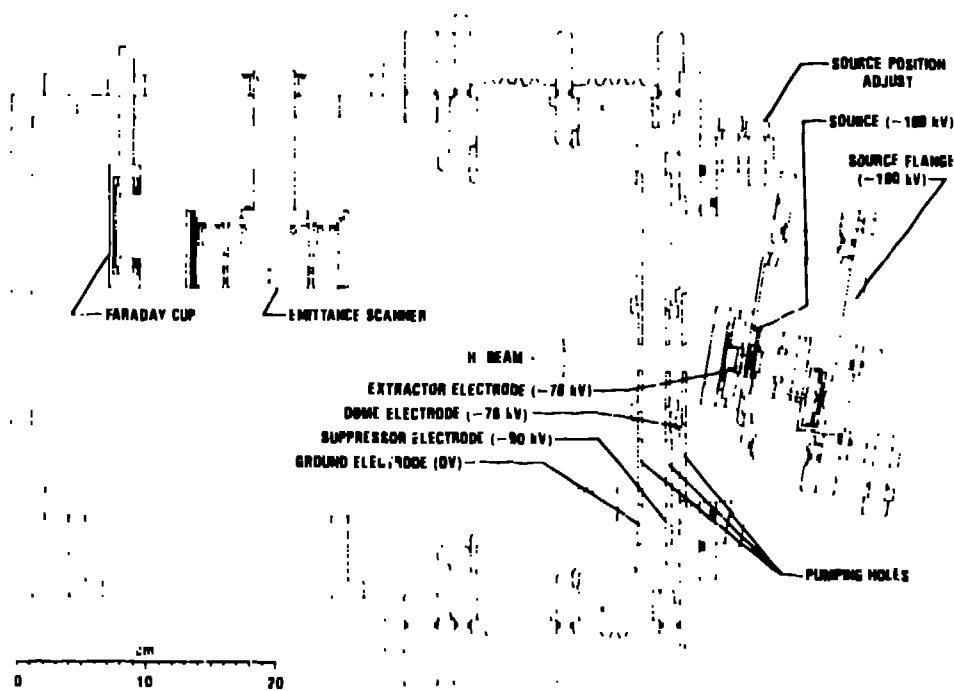


Fig. 7. Layout of the revised 100-keV injector.

to the Faraday cup increased by 20-100% when xenon was used in the beamline at a density of  $\sim 10^{12}/\text{cm}^3$ ; however, emittance in both planes grew by 20-90%, probably because of the change in the first-order transport optics, as observed by substantial rotations of the X- and Y-plane emittances. This change has evidently led to increased third-order aberrations in the column. The Y-plane emittance was about equal to the 20-keV measurement, but the X-plane value was substantially larger, never being less than  $0.019 \text{ }^{\circ} \text{ cm/mrad}$ . With zero xenon density, we measured emittances of  $0.021$  by  $0.023 \text{ }^{\circ} \text{ cm/mrad}$  in the Y- and X-planes having a measured current of slightly over 100 mA.

#### CONCLUSION

A Penning source with a small bend angle has been used to produce a 100-keV beam of high brightness. The nature of beam-transport instabilities leading to demagnetization and emittance growth is not fully understood and is under further investigation.



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